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VALORIZING POTATO PEEL WASTE BIOREFINERY CONCEPT

Valorización de los residuos de cáscara de papa mediante el concepto de biorrefinería

Valorização dos resíduos da casca de batata através do conceito de biorefinaria

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ABSTRACT

The industrial conversion of agricultural products generates waste biomass with high potential to obtain value-added products. The industrial processing of potatoes creates large amounts of waste with high phenolic and structural polymer content, such as cellulose and starch. Several studies have evaluated different pathways to valorize waste biomass from the potato industry into a series of value-added products and energy vectors at lab-scale. Nevertheless, few studies have analyzed the prefeasibility of implementing these alternatives on an industrial scale. This work aimed to determine the technical and economic prefeasibility of valorizing potato peel waste as an alternative to be implemented in Colombia. The study was divided into three stages: literature review, biorefinery design and simulation, and techno-economic analysis. The results show that 3.7 mg/g d.b. of chlorogenic acid, 179.8 L/ton of ethanol, and 256 ml of biogas/g VS can be produced from potato residues. The biorefinery is feasible at scales over 100 tons/h and can be implemented in the Boyacá region of Colombia. However, the analysis should consider logistical factors to reduce uncertainty in the proposed schemes.

KEYWORDS

Waste valorization, biorefinery, phenolic compounds, biofuels, techno-economic analysis.

RESUMEN

La conversión industrial de productos agrícolas genera residuos de biomasa con un alto potencial para obtener productos de valor agregado. El procesamiento industrial de la papa genera grandes cantidades de residuos con alto contenido de polímeros estructurales como celulosa y almidón y fenólicos. Varios estudios han evaluado diferentes vías para valorizar la biomasa residual de la industria de la papa en una serie de productos de valor agregado y vectores energéticos a escala. Sin embargo, pocos estudios han analizado la prefactibilidad de implementar estas alternativas a escala industrial. Este trabajo tuvo como objetivo determinar la prefactibilidad técnica y económica de la valorización de residuos de cáscara de papa como una alternativa a implementar en Colombia. El estudio se dividió en tres etapas: revisión bibliográfica, diseño y simulación de biorrefinería y análisis tecno económico. Los resultados muestran que a partir de la cáscara de papa se pueden producir 3,7 mg/g b.s. de ácido clorogénico, 179,8 L/tonelada de etanol y 256 ml de biogás/g SV. La biorrefinería es factible a escalas superiores a 100 toneladas/h y puede implementarse en la región de Boyacá, Colombia. Sin embargo, el análisis debería considerar factores logísticos para reducir la incertidumbre en los esquemas propuestos.

PALABRAS CLAVE

Valorización de residuos, biorrefinería, compuestos fenólicos, biocombustibles, análisis tecnoeconómico.

RESUMO

A conversão industrial de produtos agrícolas gera biomassa residual com alto potencial para obter produtos de valor agregado. O processamento industrial de batatas gera grandes quantidades de resíduos com alto teor de polímeros fenólicos e estruturais, como celulose e amido. Vários estudos avaliaram diferentes caminhos para valorizar a biomassa residual da indústria da batata em uma série de produtos de valor agregado e vetores de energia em escala. No entanto, poucos estudos analisaram a pré-viabilidade de implementar essas alternativas em escala industrial. Este trabalho teve como objetivo determinar a pré-viabilidade técnica e econômica da valorização de resíduos de casca de batata como uma alternativa a ser implementada na Colômbia. O estudo foi dividido em três etapas: revisão da literatura, desenho e simulação da biorrefinaria e análise técnico-económica. Os resultados mostram que 3,7 mg/g b.s. de ácido clorogênico, 179,8 L/ton de etanol e 256 ml de biogás/g VS podem ser produzidos a partir de resíduos de batata. A biorrefinaria é viável em escalas superiores a 100 toneladas/h e pode ser implementada na região de Boyacá, na Colômbia. No entanto, a análise deve considerar fatores logísticos para reduzir a incerteza nos esquemas propostos.

PALAVRAS-CHAVE

Valorização de resíduos, biorrefinaria, compostos fenólicos, biocombustíveis, análise tecnoeconômica.

Highlights

- Bioethanol makes the valorization of potato peel waste unfeasible - The bioethanol production yield from potato waste was 179 L/ton. - The chlorogenic acid extraction makes the valorization of potato peel waste feasible. - The minimum scale for economic viability of the potato waste biorefinery is 0.13 ton/h on a dry basis.

Introduction

Potato (*Solanum tuberosum* L.) is one of the most important agricultural products for human food worldwide, after rice and wheat, according to the FAO (Campos and Ortiz, 2019). China leads world potato production ranging from 66 to 76 million metric tons/yr (Wang et al., 2023). Colombia does not occupy a relevant position in the world ranking of potato-producing countries (Martínez-Maldonado et al., 2021). Colombia produced 3.7 million tons of this agricultural product in 2021, with an average national yield of 15.88 ± 6.04 tons per hectare (MinAgricultura, 2022). This agricultural product has become essential in Colombian consumption. Moreover, potato is part of the basic family shopping food basket. This fact can be reflected in the per capita consumption of potatoes, which is 57 kg/yr. Approximately, 90% of potatoes are consumed fresh. Meanwhile, the remaining 10% is upgraded into food products (e.g., frozen fries, mashed potatoes, and snacks). The potato industry is crucial to the Colombian economy, providing around 264,000 jobs and contributing 3.3% to the national agricultural GDP (MinAgricultura, 2022).

The industrial processing of potatoes generates a large amount of waste such as peels and off-grade potatoes. These residues represent 10% - 15% of the tuber's weight (Jimenez-Champi et al., 2023). Colombia, in the regions of Cundinamarca, Boyacá, and Nariño has a theoretical potato peel waste generation capacity of 12,260 tons/yr, 9,400 tons/yr, and 7,950 tons/year, respectively, with a total production capacity of 33,980 tons/yr (MinAgricultura, 2022). These wastes currently have no commercial or added value since they are not subjected to any transformation process. On the contrary, the transport and disposal of this waste generate costs for the industries. On the other hand, the disposal of potato peels and off-specification products in landfills contributes to climate change since the organic matter decomposition produces greenhouse gases (e.g., methane and carbon dioxide) and leachates with high organic loads. It is essential to evaluate various waste recovery methods to expand the product range of the potato value chain, boost the economic growth of the industrial sector, and reduce the environmental impact of solid waste disposal.

Potato peels have been extensively investigated as a potential raw material for value-added products based on their content of structural polymers such as cellulose and starch. Indeed, Cao et al. (2022) reported a biohydrogen production of 60.2 mL H_2/g feedstock through dark fermentation of potato peels at 37 °C, pH 7.0, and 120 rpm. Liang et al. (2014) reported a lactic acid production yield of 0.25 g/g of raw material in a culture of Lactobacillus cassei in batches at 35 °C. Escanciano et al. (2023) reported succinic acid production with a concentration of 32.2 g/L and a productivity of 0.64 g/L/h using Actinobacillus succinogenes DSM 22257. Similar studies searching for the valorization of potato peel waste have been reported in the literature at the laboratory level (Felekis et al., 2023). In addition to the C6 structural polymer fraction, this type of residue has been widely recognized as a source of phenolic compounds, especially chlorogenic acid, which have been extracted

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through different technologies such as microwaves, ultrasound, supercritical fluids, agitation with eutectic solvents. Chlorogenic acid (CGA) stands out for its wide range of health benefits and industrial applications, particularly in the food and nutraceutical sectors. Its biological properties—including antioxidant, hepatoprotective, antibacterial, and potential anti-tumor effects—position CGA as a valuable compound for managing obesity and diabetes through the regulation of glucose and lipid metabolism (Nguyen et al., 2024). For example, Andrade-Lima et al. (2021), reported chlorogenic acid and caffeic acid extraction from potato peel waste through supercritical fluids. Indeed, these authors performed these phenolic acids extraction using CO_2 and methanol as solvent and cosolvent at 80 °C, 350 bar, 20% v/v in methanol, and a flow rate of 18 g/min.

The extraction yields obtained were 3.87 mg/g (d.b.) and 0.75 mg/g (d.b.), respectively. Other authors have reported optimal extraction conditions by applying different technologies (Frosi et al., 2021). Microwave-assisted extraction can be performed at 80 °C, 2 min, 1:40% w/v, 300 W, 120 rpm, using ethanol as solvent at a concentration of 60% v/v (Wu et al., 2012). Ultrasound-assisted extraction has been reported to use 83# glycerol, 80°C, 90 minutes, 1,81% p/v, 37 kHz, 140 W, and 35% w/v (Frosi et al., 2021). Finally, conventional extraction using 50% v/v ethanol, 60°C, 1 h, and a solid-liquid ratio of 1:20 (Silva et al., 2021). On the other hand, energy carriers such as bioethanol and biogas production have also been proposed from potato peel waste. Soltaninejad et al. (2022) reported the simultaneous production of bioethanol and biogas using potato peel waste as feedstock. These authors performed organic solvent pretreatment of the feedstock using 50-75% v/v of an ethanol solution catalyzed with 1% w/w sulfuric acid. The yields obtained from 1 kilogram of dry raw material were 539.8 g of glucose, 224.2 g of bioethanol, and 57.9 L of methane.

Despite the promising potential of potato peel waste, few studies have investigated its integration into a scalable biorefinery framework. This review proposes a biorefinery model for the comprehensive valorization of potato peel waste, focusing on chlorogenic acid, bioethanol, and biogas production. It also provides a technical assessment for its implementation in the Colombian context. A process simulation using SuperPro Designer Demo Version was performed to calculate mass and energy balances for each unit operation, accompanied by a comprehensive review of alternative valorization strategies.

Materials and methods

A systematic review was conducted to analyze existing literature on the composition of potato peels and their variability. Indeed, the present study used the chemical composition reported by Soltaninejad et al. (2022). The biorefinery was proposed following the methodology of the conceptual design of biorefineries presented by Moncada et al., (2014). Material and energy balances were estimated by modeling and simulation tools such as Matlab and SuperPro Designer Demo Version software. Then, a techno-economic analysis was conducted using the mass, energy, and financial indicators as reported by Alonso-Gómez et al. (2020).

Raw material, process scale, and assumptions

The raw material used is potato peels, which have the chemical composition reported in Table 1. The potato peel composition is reported on a wet basis since these residues have a high moisture content (Cao et al., 2022). In this sense, the chemical composition of the raw material was standardized to consider this moisture value. The biorefinery processing scale was selected based on potato production in Colombia in 2021. Agronet's production statistics reflect a potato production of 1.25 million tons in 2021. 10% of the potato is used at the industrial level (MinAgricultura, 2022). Therefore, 0.12 million tons are industrially processed per year.

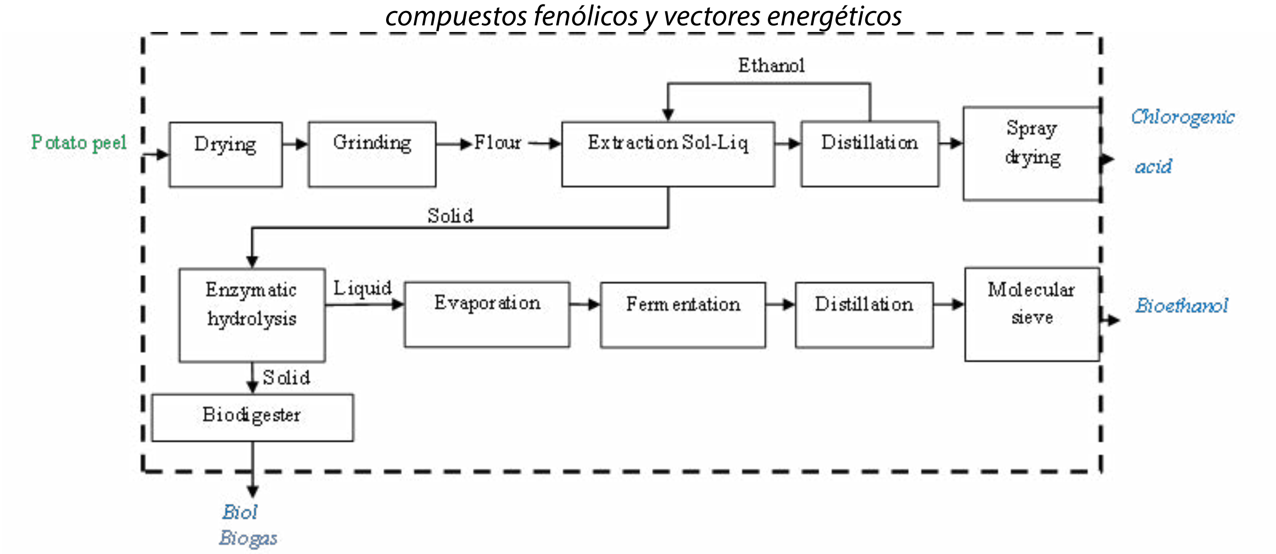
Table 1. Proximal composition of potato peels
Tabla 1. Composición proximal de las cáscaras de papa

Component	Content (% w/w)	
	Wet basis	Dry basis
Moisture	80.00	10.00
Extractives	4.35	19.59
Cellulose	5.34	24.01
Starch	5.05	22.75
Hemicellulose	1.28	5.76
Lignin	1.89	8.49
Protein	1.95	8.78
Lipids	0.12	0.54
Ash	0.02	0.09
Total	100.00	100.00

Fuente: elaboración propia en base a Soltaninejad et al. (2022). Source: own elaboration based on base a Soltaninejad et al. (2022).

Additionally, potato peels account for 10% w/w, generating a feedstock quantity of 12,257 tons. The process block diagram of the proposed biorefinery is presented in Figure 1.

Figure 1. Block diagram of potato peel biorefinery to produce phenolic compounds and energy vectors
Figura 1. Diagrama de bloques de la biorrefinería de cáscara de papa para la producción de compuestos fenólicos y vectores energéticos



Fuente: elaboración propia. Source: own elaboration.

The following are the assumptions considered within the simulation process:

A. The composition of potato peels does not vary over time due to microbiological action. Therefore, the chemical composition remains unmodified from its generation until it is taken to the biorefinery. This statement refers to the potential decomposition of the raw material (i.e., potato peels) in previous stages such as collecting and storage. Indeed, the high moisture content indicates a high water activity. Thus, several microorganism can attack the potato peel until degrade most of the structural components.

B. The location of the biorefinery and all logistical aspects related to the harvest, transportation, and storage of potato peels were not considered to increase the number of variables to be considered and the uncertainty of the biorefinery. This statement was made to evidence the scope of the techno-economic assessment since the biorefinery analysis was made without consider the raw materials transport, storage, and conditioning costs. Moreover, logistics aspects related to the type of vehicle were not considered.

C. The biorefinery operates 350 days with three 8-hour shifts. Therefore, the biorefinery's base flow of feedstock is 1.46 wet tons/hr. This statement was proposed to consider a continuous facility.

D. The technological maturity level of the unit operations and processes is at the implementation stage (i.e., TRL 9).

E. The biorefinery is considered a "Greenfield" process. Therefore, land acquisition and building construction aspects are considered in the economic analysis.

Process description

Raw material conditioning

The potato peels are dried using a rotary drum dryer operating at a temperature of 50 °C. This reduces the moisture content of the raw material from 80% to approximately 10%. After drying, the raw material is ground to 40 mesh (0.45 mm) using two blade mills in series. The material is conditioned to reduce water activity and then stored for later use.

Chlorogenic acid extraction

The extraction of chlorogenic acid was performed using an extraction column with five theoretical stages to remove the maximum number of phenolic compounds present in potato peels. The solvent used in the extraction is ethanol, which has been recognized as a safe solvent that can be used for the extraction of metabolites for pharmaceutical, cosmetic, and food applications. The optimal conditions for the extraction process were those reported by Rodriguez-Amado et al. (2014). The extraction conditions of temperature, contact time, solid-liquid ratio, and ethanol concentration were: 90 °C, 30 min, 1:20 by weight, and 70% v/v. After the extraction, we recovered the solvent (ethanol) using a distillation column. Subsequently, the chlorogenic acid stream is dried using a spray dryer. Thus, the final product of the production process is a chlorogenic acid powder with 99% purity. The solvent recovery process is designed to recover 90% of the ethanol used in the extraction process.

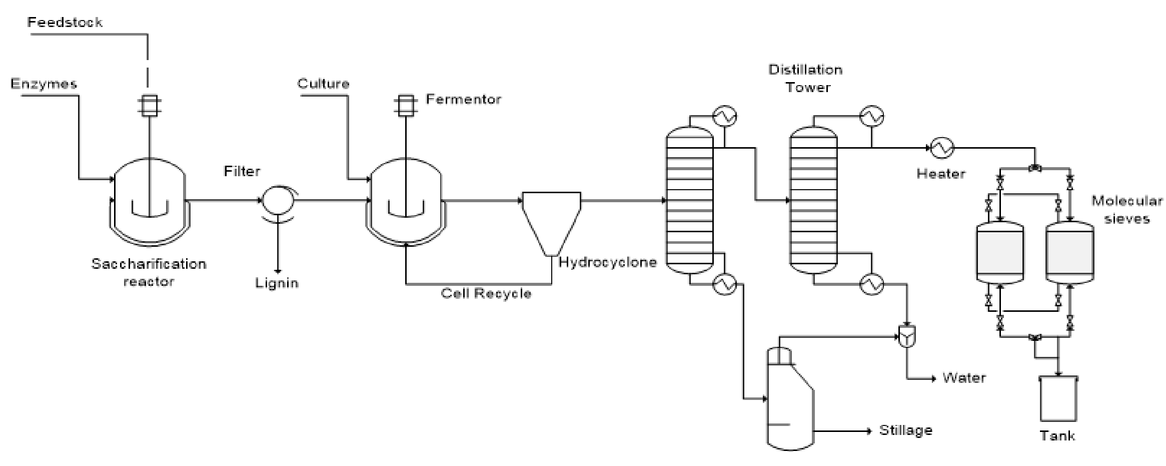
Bioethanol production

The solid resulting from the phenolic compound extraction process is used in bioethanol production. This production process is divided into three stages (i) enzymatic hydrolysis, (ii) fermentation, and (iii) separation/purification.

The enzymatic hydrolysis stage seeks to produce glucose from the breakdown of starch (amylose and amylopectin) and cellulose by enzymatic action. Enzymatic hydrolysis is carried out at 50°C for five hours (Barati et al., 2019). An enzyme cocktail called Viscozyme L is used. This cocktail is a multi-enzyme complex with a wide range of carbohydrases, including arabinase, cellulase, β-glucanase, hemicellulase, and xylanase (Barati et al., 2019). This enzyme cocktail promotes the hydrolysis and saccharification of starch, cellulose, hemicellulose, and pectin by breaking down the non-degradable material into soluble sugar molecules (i.e., glucose). The enzyme loading used in the process was 15 FPU/g of C_6 polymer in the raw material (i.e., cellulose and starch). The hydrolysis efficiency of these fractions is assumed to be 82% according to previous experiences in enzymatic hydrolysis processes (Yu et al., 2018). After the enzymatic hydrolysis process, a glucose-rich hydrolysate and a solid fraction containing materials such as lignin, protein, and unconverted fractions of structural polymers (i.e., cellulose, hemicellulose, lignin, and starch) are separated. The liquid fraction is concentrated using an evaporator to a glucose concentration of 110 g/L, while the remaining solid is used for biogas production.

The Saccharomyces cerevisiae strain is used for bioethanol and CO_2 production through glucose consumption during fermentation at 30 °C. The bioethanol production process flow diagram is shown below in Figure 2.

Figure 2. Process to produce bioethanol from potato peelings
Figura 2. Proceso de producción de bioetanol a partir de cáscaras de papa



Fuente: elaboración propia. Source: own elaboration.

Fermentation is carried out in a continuous stirred tank fermenter. In this stage, the conversion of sugars into bioethanol takes place. Modeling of this process is usually performed using non-segregated and unstructured models (i.e., Monod-type kinetics). This model is commonly used under the assumption that there is no product or substrate inhibition. Therefore, more complex kinetic models, such as the one proposed by Jarzebski et al. (1992), are required. The model proposed by these authors belongs to the simple unstructured segregated type. The kinetics are presented in equations (1), (2), and (3):

$$\mu_v = \mu_{max} \frac{S}{K_1 + S} \left(1 - \frac{P}{P_c} \frac{S}{K_2 + S}\right) \quad (1)$$

$$\mu_{nv} = \mu'_{max} \frac{S}{K_1 + S} \left(1 - \frac{P}{P'_c} \frac{S}{K_2 + S}\right) - \mu_v \quad (2)$$

$$\mu_d = - \mu_v \quad (3)$$

Where: μ_v is the viable cells concentration [g/L], μ_{nv} is the non-viable cells concentration [g/L], μ_d is the dead cells concentration [g/L], μ_{max} is the maximum growth rate of viable cells [h^{-1}], μ'_{max} is the maximum growth rate of non-viable cells [h^{-1}], P is the bioethanol concentration [g/L], P' is the limiting ethanol concentration for non-viable cells [g/L], S is the substrate concentration [g/L], K_1 y K_2 are saturation constants [g/L].

The growth rate can be coupled to the balances of a fermenter to elucidate the concentration profiles of biomass, substrate, and product. The differential equations associated with these balances can be seen in equations (4), (5), (6), (7) and (8):

$$\frac{dS}{dt} = D(S_o - S) - \frac{\mu_v}{Yxs} x_v - m_s x_{nv} \quad (4)$$

$$\frac{dP}{dt} = D(P_o - P) + \frac{\mu_v}{Yxp} x_v + m_p x_{nv} \quad (5)$$

$$\frac{dx_v}{dt} = D\left(x_{v_o} - x_v\right) + \left(\mu_v - \mu_{nv} - \mu_d\right) x_v \quad (6)$$

$$\frac{dx_{nv}}{dt} = D\left(x_{nv_o} - x_{nv}\right) + \mu_{nv} x_v - \mu_d x_{nv} \quad (7)$$

$$\frac{dx_d}{dt} = D\left(x_{d_o} - x_d\right) + \mu_d (x_v - x_{nv}) \quad (8)$$

Where: D, is the dilution rate [h^{-1}], x_v, is the concentration of viable cells [g/L], x_{nv}, is the concentration of non-viable cells [g/L], x_d, is the concentration of dead cells [g/L], Y_{xp}, is the yield of the product relative to the substrate, Y_{xs}, is the yield of the substrate relative to the biomass.

After fermentation, a hydrocyclone is utilized to mix the fermenter cells and improve bioethanol production. The bioethanol is then separated through a system of distillation towers and a molecular sieve. The first distillation tower is the exhaustion column, which removes excess water and impurities like cells and metabolites. This process produces a 50% v/v distillate. Next, the rectification occurs, during which the bioethanol is concentrated to its azeotropic point. (i.e., 95% w/w). This tower generates more stillage, which is finally blended in the process. Finally, molecular sieves are used to dehydrate the bioethanol. The operating conditions used in the process are those reported by Quintero et al. (2011).

The distillation towers for each process were designed using abbreviated methods. The empirical Fenske equations were used to calculate the minimum number of stages (Nmin) required for separation, and the Underwood equations were used to calculate the minimum reflux ratio (Rmin). These equations (9), (10), and (11) are presented as follows:

$$N_{min} = \frac{\log\left(\frac{x_{LK,D}}{x_{LK,B}} \frac{x_{HK,B}}{x_{HK,D}}\right)}{\log\left(\bar{\alpha}_{LK,HK}\right)} \quad (9)$$

Where: $x_{LK,D}$, is the molar composition of the light component in the distillate stream, $x_{HK,B}$, is the molar composition of the heavy component in the vinasse stream of, $x_{LK,B}$, is the molar composition of the light component in the vinasse stream $x_{HK,D}$, is the molar composition of the heavy component in the distillate stream, and $\bar{\alpha}_{LK,HK}$, is the geometric mean of the relative volatility of the heavy component concerning the light component.

$$\frac{\Delta V}{F} = \sum \frac{\bar{\alpha}_{i,HK}\, x_{i,F}}{\bar{\alpha}_{i,HK} - \emptyset} \quad (10)$$

Where: ΔV, is the variation of the steam flow rate generated in the boiler, and F is the molar flux in the feed zone. From equation (10), the value of "∅" was obtained and the minimum reflux ratio was calculated from the equation proposed by Underwood.

$$R_{min} = \sum \frac{\bar{\alpha}_{i,HK}\, x_{i,F}}{\bar{\alpha}_{i,HK} - \emptyset} - 1 \quad (11)$$

Finally, once the Nmin and Rmin values are found, the 1.25 Nmin ratio is applied to determine the reflux ratio of each of the towers of each process.

Finally, once the Nmin and Rmin values are found, the 1.25 Nmin ratio is applied to determine the reflux ratio of each of the towers of each process.

Biogas production

The biogas production process was simulated considering the chemical composition of the exhausted solid after the enzymatic hydrolysis. The Buswell equation was used to predict the theoretical methane production potential based on the initial composition of the exhausted solid. The efficiency of the reaction was assumed to 65% since lignin has a low degradation rate under anaerobic conditions. The anaerobic digestion process was simulated considering mesophilic conditions (35°C). An anaerobic sludge was used as inoculum. The hydraulic retention time was adjusted to 25 days based on different literature reports. The organic matter load was based on the volatile solids ratio between the substrate and inoculum. Thus, this ratio was adjusted to 0.4. Raw biogas was subjected to a upgrading process to remove hydrogen sulfide and moisture. Then, the biogas was used as fuel to produce heat and power in a cogeneration system.

Techno-economic analysis

The technical analysis of the biorefineries involved the implementation of mass and energy efficiency indicators (Ruiz-Mercado et al., 2012). Matter and energy balances were obtained from the SuperPro Designer software. The formulas of the missing components within the software (e.g. cellulose and lignin) were entered into the software as a new compound. Additionally, some thermodynamic properties were entered according to reports made by the National Renewable Energy Laboratory (NREL) of the United States of America (Wooley and Putsche, 1996).

When evaluating the performance of a biorefinery, three mass indicators are typically used: yield, process mass intensity, and renewability index. Additionally, energy indicators are evaluated to determine the energy requirements of the process and the total energy balance. The indicators are derived from the material and energy balances of each operation and unit process in the biorefinery, as well as the energy requirements for service fluids. However, energy integration and the design of a heat exchange network are not considered.

Mass efficiency indicators

The mass efficiency indicators calculated were product yield (Yp), and process mass intensity index (PMI). These indices are used in green chemistry to evaluate the transformation of different raw materials (Ruiz-Mercado et al., 2012). Yp is defined as the ratio between the products obtained and the main raw material used in the process (potato peels) (Alonso-Gómez et al., 2020). Yp was calculated using equation 12 (Cardona Alzate et al., 2018).

$$Y_P = \frac{\sum \dot{m}_{\text{Product, i}}}{\dot{m}_{potato}} \tag{12}$$

Where Yp was product yield; $\dot{m}_{\text{Product}}$ was product mass flow, (i), [kg h^{-1}]; $\dot{m}_{\text{potato}}$: potato peel mass flow, [t h^{-1}].

The PMI (Process Mass Intensity) is estimated as the ratio of all input streams to the desired products. This indicator helps calculate and improve the yield of raw materials used in the process. Additionally, PMI can be utilized to identify the most efficient raw material transformation route and to develop more productive processes. PMI was calculated using the equation 13 (Ruiz-Mercado et al., 2012).

$$\text{PMI} = \frac{\sum_{i=1}^{N} \dot{m}_i^{in}}{\sum \dot{m}_{\text{Product, i}}} \tag{13}$$

Where PMI was Process Mass Intensity index; $\dot{m}_i^{in}$ was total mass flow entering the process, [kg h^{-1}]; $\dot{m}_{\text{Product}}$: product mass flow, (i), [kg h^{-1}].

Energy efficiency indicators

Energy indicators are used to assess the performance of the biorefinery. In this case, the self-generation index (SGI) was used to estimate the amount of energy supplied by the biogas production process to avoid the use of external energy sources such as natural gas, diesel, or coal. The SGI index describes the share of the energy provided by the process and the total amount of energy required. A high value of this indicators can be associated with better energy performance and low dependency of external fuels. The SGI was calculated using the equation 14.

$$SGI = \frac{(\dot{m}_{Biogas} * PCI_{Biogas}) * \eta_{Conversion}}{\dot{Q} + \dot{W}} \quad (14)$$

Where SGI was Self-Generation index (%); $\dot{m}_{Biogas}$ was Biogas mass flow; LHV was Low heating value; $\dot{Q}$ was thermal energy added to the system; W was the work added to the system; and $\eta_{Conversion}$ was the efficiency of biogas conversion in a cogeneration system.

Economic analysis

The economic analysis was conducted using the economic evaluation add-on of the SuperPro Designer simulation software. This program allows for capital cost estimation for each piece of equipment used in the biorefinery. Equipment sizing is based on the material and energy balances of each unit. Operating costs were determined by considering raw material prices, service fluid costs, as well as labor and maintenance costs, as described by Towler and Sinnott (2012). Equipment depreciation was estimated considering a 10% salvage value and the straight-line method. The interest rate and tax rate were assumed to be 33% and 9.12%, respectively (Solarte-Toro et al., 2021). The life of the project was twenty years.

The costs of raw materials, service fluids, and products generated are presented in Table 2.

Tabla 2. Precios de los insumos y condiciones económicas

Table 2 Input prices and economic conditions

	Value	Units	References
Potato peels	3.50	USD/ton	This work
Chlorogenic acid	19.00	USD/kg	(Indiamart, 2019)
Bioethanol	1.34	USD/L	(Solarte-Toro et al., 2021)
Process water	0.33	USD/m3	(García-Velásquez and Cardona, 2019)
Electricity	0.14	USD/kW	
Low-pressure steam	7.89	USD/Ton	
Medium pressure steam	8.07	USD/Ton	
Enzymes	49.30	USD/kg	
Cooling water	0.042	USD/m3	

Fuente: elaboración propia. Source: own elaboration.

Results and discussion

The simulation results are analyzed in terms of mass, energy, and economic indicators. Furthermore, a comparison is drawn with the existing literature to determine the range of values given, as no studies have examined the analysis of a biorefinery like the one proposed in this scientific paper.

Mass analysis

The efficiency of converting raw materials into products was assessed by estimating yield, process mass intensity, and renewability index. Chlorogenic acid, bioethanol, and biogas yields were 3.17 mg/g, 170 L/ton, and 256 ml biogas/g feedstock, respectively. These yields can be compared with the literature. The recovery of chlorogenic acid is lower than that obtained by Nathia-Neves et al. (2021) which obtained a Yp of 8.4 mg/g of material by microwave-assisted extraction, the raw material being sunflower cake. The bioethanol yield of 170 L/ton is within the range for lignocellulosic materials, such as potato peel, for example, from coffee husks, Yp between 130 and 470 L/ton of coffee husks were obtained (Burniol-Figols et al., 2016). These results are superior to those obtained with green bananas Yp of 71 L/ton unripe plantain (Alonso-Gómez et al., 2020) but lower than the Yp of 250 71 L/ton of green banana peel. The biogas yield is high compared to other studies such as that of Burbano-Cuasapud et al. (2023), who report a Yp of 0.101 g biogas/g feedstock, considering that biogas is a product that has the possibility of being reintroduced into the process for cogeneration, it is interesting that it offers high yields.

On the other hand, the mass intensity of the process was estimated at 72.68 kg of raw material/kg of products. This indicator was estimated without considering the amount of process water used in the biorefinery. All other inputs such as ethanol, potato peels, and enzymes were considered. This indicator allows us to elucidate the transformation of raw materials into the desired products. In this sense, the PMI should tend to unity. Thus, very high values of this indicator show shortcomings in the production process and the need to change technologies or carry out mass integration processes (i.e., process intensification). Various authors have reported values for PMI estimation. For example, Tobiszewskiet al. (2015) reported that for processes focused on bulk chemical production. The PMI can range from 5 – 50, therefore, the process can be subject to mass optimization to reduce the consumption of raw materials. The PMI is highly affected by the extraction stage due to the large volumes of solvents used in this process. Thus, the extraction of chlorogenic acid should be considered with lower solid-liquid ratios (i.e., 1:10) or new process alternatives that minimize the use of solvents as much as possible (e.g., microwaves, ultrasound, supercritical fluids).

Ruiz-Mercado et al. (2013), reported that a process can be considered to have poor mass efficiency if the input product flow is 40 times higher than the output product flow. However, this range is wide to evaluate the processes. In the case of the biorefinery, the raw material input flow is 14.5 times greater than the product output flow. Even if it is considered that all the bioethanol is recirculated to the process, and only chlorogenic acid is produced, there is a flow of raw material that is 28 times greater than the flow of products. These situations show that the range proposed by Ruiz-Mercado et al. (2013) is wide and should be taken with caution if the PMI value is within the established limits, it does not make it an efficient process in mass terms. On the other hand, the PMI of the bioethanol production process (only considering the input flow of extracted potato peels and enzymes) was 32.6 kg/kg. This indicator is lower than that reported by Alonso-Gomez et al, (2020). These authors reported a PMI value for bioethanol production from plantain of 41.23 kg/kg. This difference in the values obtained is because no type of pretreatment (e.g. dilute acid) was used. Therefore, the input demands of the process are lower. Agro-industrial wastes high in starch, like potato peels, can be repurposed using technology developed for lignocellulosic materials. Potato peels, avocado seeds, and shredder residues could become valuable products through fermentation processes. The process's renewability index was only 10.34%, meaning that the amount of renewable feedstock (potato peel) used was very low compared to the total inputs required. Therefore, adjustments to the process must be made to increase the proportion of renewable feedstock. Recycling all bioethanol into the chlorogenic acid extraction process increases the renewability rate to 39.98%. It's important to evaluate options economically and environmentally to determine the best process configuration.

Energy analysis

The SGI was estimated to determine the amount of energy that could be derived from the production and use of biogas in the potato peel biorefinery. The SGI for the biorefinery was 12%. Therefore, the consumption of service fluids (i.e., steam and electricity) can be decreased somewhat. The low value in the SGI is attributed to the low yield of biogas production from the already extracted and hydrolyzed potato peels. Indeed, the yield of 256 L/g feedstock is low with other values reported in the literature (Iyer & B, 2022). Also low compared to other raw materials such as orange peel and whey (Ortiz-Sanchez et al., 2020).

Economic analysis

The proposed biorefinery has a total capital investment of $15.12 M.USD including all processing lines for chlorogenic acid, bioethanol, and biogas production. The total investment cost is in line with values reported in other research involving similar production processes (Solarte-Toro et al., 2019). The capital costs found can be extrapolated to the results found by other researchers with larger or smaller scales of production by applying the scaling factor of 0.6 (Romero-García et al., 2016; Towler & Sinnott, 2012). However, the capital costs estimated in this study constitute a conceptual engineering basis, which implies that the results can be classified as class V economic data (Solarte-Toro et al., 2021). This type of result has a low precision because the reported values can change by more than 50%. Nevertheless, the results demonstrate the feasibility of this type of process. The bioethanol production plant accounted for 67% of the total investment costs, while chlorogenic acid extraction and biogas accounted for 25% and 8%, respectively. This trend can be explained by the number of processes considered in the economic analysis. Similar results related to the distribution of capital costs have been reported in the literature for different types of processes, where the greater the number and complexity of the technologies used in the production processes, the higher the cost (Kapanji et al., 2021).

Plant operating costs involve the estimation of feedstock, maintenance, depreciation, and labor costs. Feedstock constitutes 83% of the plant's operating costs due to the use of ethanol as a solvent in the extraction process even though it is almost entirely recovered in the biorefinery. The ethanol used in the extraction process makes up 95% of the raw material acquisition costs, while the remaining 5% is distributed in the acquisition of enzymes and raw materials. Capital depreciation constituted 12% of total operating costs due to the high number of operations and unit processes that were contemplated within the biorefinery. Specifically, the bioethanol production plant had the highest share in capital depreciation, as well as in the case of capital costs, followed by the chlorogenic acid and biogas extrac-

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tion plant. Finally, maintenance and labor costs were low. The estimated labor force for the production plant was 25 employees. The total operating cost for these two items was 0.09 M.USD. Three factors contribute to this value being so low compared to the other items considered (i.e., depreciation and raw materials). The process requires high volumes of raw materials to transform 1.46 tons/h into the desired products. The second factor is related to the number of jobs calculated through mathematical relationships such as those reported by Peters and Timmerhaus (2003).

Indeed, the ratios for estimating the number of jobs generated do not reflect the reality of a company operating with high volumes of raw materials. Finally, the third factor is associated with the payment of labor in Colombia. Employees in Colombia receive a minimum wage that is much lower than what can be found in other economies in the world, more specifically in Latin America. The low value of labor remuneration makes it possible for some processes to be easily carried out in the Colombian context.

The proposed biorefinery did not achieve economic viability at the proposed scale and does not break even (i.e., a net present value equal to 0) at any scale. This is because the economic potential of the process is always negative. The ethanol consumed in the chlorogenic acid extraction is always greater than the anhydrous bioethanol produced. All produced bioethanol must be recycled back into the process area, and the only product commercialized in the biorefinery is chlorogenic acid. As a result, bioethanol production negatively impacts the biorefinery due to its high capital investment costs and zero-income from bioethanol production. Therefore, other valorization routes for the fraction of C6 structural polymers that make up potato peels should be proposed. One processing alternative is the generation of high-value-added products such as succinic acid or levulinic acid, which have high commercialization costs (around 5 USD/kg) (Escanciano et al., 2023).

If the bioethanol production part is eliminated, the capital costs of the process drop to 4.96 million USD, and the break-even point is reached after 5 years. Smaller scales of potato peel waste valorization may be considered for chlorogenic acid and biogas production. The minimum scale of processing for economic viability is 0.13 ton/h. This can be achieved in Cundinamarca, Boyacá, and Nariño. Producing phenolic compounds from potato peels is a viable alternative. The selection of products within a biorefinery must be carefully analyzed to avoid negative impacts on the process.

Conclusions

Potato peel waste is a potential raw material for the generation of high-value-added products due to its high content of extracts, starch, and cellulose. Therefore, different lines of processing and valorization should be investigated. The simultaneous production of chlorogenic acid, bioethanol, and biogas is not economically viable at any production scale due to the high cost of the raw materials used in the extraction process. Thus, the proposed biorefinery is not feasible and should not be considered in future project design and formulation. However, the joint production of chlorogenic acid and biogas is a viable alternative for its implementation in the real context, since the scales required for its economic viability can be applied in the contexts of the departments of Cundinamarca, Boyacá, and

Nariño. The minimum scale of processing for economic viability was 0.13 ton/h. Finally, the self-generation rate of the process increased to 47% when bioethanol production was avoided. This leads to the conclusion that bioethanol generation still needs to be studied and improved despite raw materials rich in starch and cellulose.

Prospective

The production of phenolic compounds from potato peels can be a cost-effective alternative. Analyzing and comparing extraction technologies can be a valuable research area. Biogas production from potato peel waste can reduce energy consumption, cut fossil fuel use, and promote energy diversification. Utilizing potato peels for the sugar platform needs consideration for economic and environmental factors, focusing on starting from research levels for various products.

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